EFFECTS OF TIME-DEPENDENT MOISTURE CONTENT OF SURFACE SEDIMENTS ON AEOLIAN TRANSPORT RATES ACROSS A BEACH, WILDWOOD, NEW JERSEY, U.S.A.

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Received 31 July 1995; Revised 24 May 1996; Accepted 12 June 1996

ABSTRACT

A one-day field investigation on an unvegetated backbeach documents the importance of surface sediment drying to aeolian transport. Surface sediments were well sorted fine sand. Moisture content of samples taken in the moist areas on the backbeach varied from 2·9 to 9·2 per cent. Lack of dry sediment inhibited transport prior to 08:50. By 09:10 conspicuous streamers of dry sand moved across the moist surface. Barchan-shaped bedforms, 30 to 40 mm high and composed of dry sand (moisture content <0·10 per cent), formed where sand streamers converged. The surface composed of dry sand increased from 5 per cent of the area of the backbeach at 09:50 to 90 per cent by 12:50.

Mean wind speeds were between 5·6 and 8·6 m s^{-1} at 6 m above the backbeach. Corresponding shear velocities were always above the entrainment threshold for dry sand and below the threshold for the moist sand on the backbeach. Measured rates of sand trapped (by vertical cylindrical traps) increased during the day relative to calculated rates. The measured rate of sand trapped on the moist foreshore was higher than the rate trapped on the backbeach during the same interval, indicating that the moist foreshore (moisture content 18 per cent) was an efficient transport surface for sediment delivered from the dry portion of the beach upwind.

Measured rates of sand trapped show no clear relationship to shear velocities unless time-dependent surface moisture content is considered. Results document conditions that describe transport across moist surfaces in terms of four stages including: (1) entrainment of moist sediment from a moist surface; (2) *in situ* drying of surface grains from a moist surface followed by transport across the surface; (3) entrainment and transport of dry sediment from bedforms that have accumulated on the moist surface; and (4) entrainment of sand from a dry upwind source and transport across a moist downwind surface. © 1997 by John Wiley & Sons, Ltd.

Earth surf. process. landforms, **22,** 611–621 (1997)
No. of figures: 7 No. of tables: 2 No. of refs: 30
KEY WORDS: wind speed; aeolian transport; sand beach; sand traps; surface moisture.

INTRODUCTION

The importance of surface moisture to aeolian sediment transport in the coastal zone is underscored in a number of field investigations (e.g. Bauer *et al.*, 1990; Kroon and Hoekstra, 1990; Wal and MacManus, 1993), but only a few studies report actual moisture data (Kuhlman, 1958; Svasek and Terwindt, 1974; Sarre, 1988). Most field investigations of sediment transport across a moist surface focus on transport after entrainment has occurred, documenting the relationship between measured rates and those calculated for dry sediment (Svasek and Terwindt, 1974; Sarre, 1988). Results show that rates over a moist sand surface approximate those over a dry surface when shear velocities are substantially higher than the threshold for dry sand. Rates over a moist surface are generally lower than rates over a dry surface at shear velocities near the entrainment threshold. There is also considerable range in measured rates of transport at low wind speeds (Svasek and Terwindt, 1974).

Part of the explanation for the variability in transport rates at low wind speeds is attributed to the spatial variation of surface moisture (Svasek and Terwindt, 1974; Sarre, 1988). The time it takes for the sand surface to dry is also important, but its measurement has been elusive owing to the complex nature of the evaporation process (Sherman, 1990a; Namikas and Sherman, 1995). Studies by Logie (1982) and Hotta *et al*. (1984)

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CCC 0197-9337/97/070611–11 $17.50

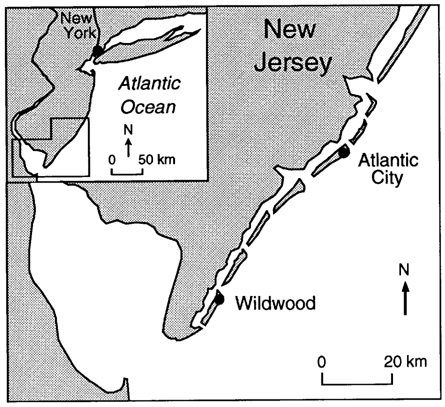

Figure 1. Location map for study area at Wildwood, NJ

show that surface drying is an important influence in environments where winds are competent to entrain dry but not moist sediments. No field studies report the time it takes for transport to become fully developed on a surface that is initially too moist for sediment entrainment.

It is possible to conceptualize five conditions that describe transport across an initially moist surface in terms of stages in the process of drying of surface sediments. In condition 1, moist sediment is entrained and transported across a moist surface; this occurs only under high-speed winds capable of entraining moist sediment. Condition 2 begins with *in situ* drying of surface grains from a moist surface followed by transport of a thin layer of dry sand across the surface, often in the form of sand streamers (Gares *et al*., 1996). This transport condition is common when the shear velocity is between the wet and dry thresholds. Transport condition 3 involves entrainment and transport of dry sediment from bedforms that have accumulated on the moist surface. The bedforms represent a secondary sediment source; they may initially form from the deposition of dry sand, as outlined in condition 2, but their presence as a large percentage of the beach surface represents a later stage in the drying process. Condition 4 involves entrainment of sand from a dry upwind source and transport across a moist surface. Condition 5 involves the entrainment and transport of sediment on a completely dry surface.

In natural environments, more than one of these transport conditions may be operative on at least a portion of the beach, and the relative importance of these may change through time. The range in transport rates for a given shear velocity and correspondence of measured to calculated rates can be explained by many factors (Nickling and Davidson-Arnott, 1990). Changes in moisture content are especially important at low wind speeds when moisture plays a relatively greater role in inhibiting entrainment. In this paper we examine sediment transport rates related to changing moisture content during relatively low wind speeds, using data gathered at Wildwood, New Jersey.

STUDY AREA

The field site (Figure 1) is located near the north end of a 10·0 km long barrier island. The area is a resort community that is used intensively by summer visitors but is virtually abandoned from October to May. The site was selected because the great width of the supratidal beach (over 200 m) and fine, well-sorted sediment sizes favour aeolian transport. The site is backed by a boardwalk and residential buildings; the meteorological mast and sampling locations were located over 130 m seaward of the structures to limit their influence on wind flow.

Mean tidal range is 1·25 m; mean spring range is 1·52 m (National Oceanic and Atmospheric Administration, 1995). Northwesterly winds prevail and are dominant in the winter months. These winds blow nearly directly offshore. Beach sediments are very well-sorted, fine sand, predominantly quartz and feldspar, with less than 5·0 per cent heavy minerals by weight (McMaster, 1954). The field deployment was conducted from 8 to 19 March 1994. Waves from the northeasterly storm of 23 February 1994 inundated the entire backbeach and reworked the surface sediments. The surface monitored on 16 March was a flat overwashed platform with little local relief

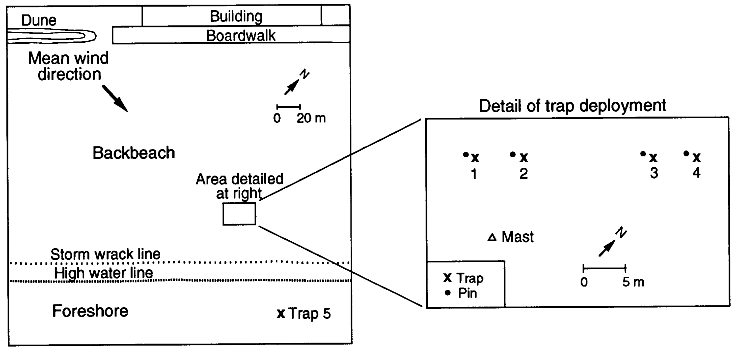

Figure 2. Location of meteorological mast and traps for investigation conducted on 16 March 1994. The wrack line depicted on Figure 2 resulted from the storm of 9 March

and no vegetation. The beach was dissipative and had a broad, flat (<1·5°) foreshore and a nearly horizontal (<0·06°) backbeach.

METHODS

The data for all days when aeolian transport occurred during the 12 day deployment are not comparable because of differences in wind direction and speed, precipitation, air temperature and relative humidity. The continuous time series collected on 16 March represents changes in transport beginning in the morning, when no transport occurred owing to low wind speeds relative to surface moisture, to a time in the afternoon when transport increased owing to higher wind speeds and increased amounts of dry sand.

Wind direction was measured using a microvane mounted at 6 m elevation on a mast located on the backbeach (Figure 2). The electronics of this vane failed, so estimates of modal wind direction were made by sighting along the vane using a hand-held compass. Wind speed was monitored at 0·25, 1·0, 2·0 and 6·0 m elevations on this mast using Gill three-cup anemometers. Air temperature and relative humidity were measured using a Campbell HMP35C probe mounted at 2·5 m elevation. Data were sampled at 1 s intervals; minimum, maximum, mean and standard deviations were calculated over 10 min intervals that corresponded to monitoring times for sand traps.

Aeolian transport was measured using vertical traps of Leatherman (1978) design, having a height above ground of 0·4 m, a 0·05 m wide opening designed to face into the wind and a 0·05 m wide opening covered with fine mesh on the opposite side. Traps were first emplaced at 09:50. Four traps were placed in a shore-parallel array 10 m upwind of the mast (Figure 2) to determine whether there were differences in transport rates alongshore. Traps 1 to 3 were removed at 12:50 so that attention could be concentrated on Trap 4, which had the least amount of scour and the greatest trapping efficiency. This trap was retained and monitored until 15:30. Trap 5 was placed on the foreshore from 14:50 to 15:10 to provide an estimate of the amount of sediment moved across the intertidal beach that had been inundated at high water and had surface sediments with greater moisture and higher salinity. The time of deployment of this trap was short because the trap required frequent attention to keep the moist sediments in transport from accumulating at the opening. The sediment in the traps and scour at the traps were monitored every 10 min throughout their deployment using a measuring stake. Measuring stake heights for each trap were converted to sand weights by comparing stake measurements with sand gathered from traps when traps were removed. The error associated with these measurement techniques is 2·0 mm for sediment in the traps and 0·5 mm for scour.

The advantages and drawbacks associated with vertical traps are discussed in Jones and Willetts (1979), Illenberger and Rust (1986) and Sherman (1990b). The traps used in this study have a reported efficiency rating of 30 to 70 per cent (Marston, 1986; Greeley *et al.*, 1996). Vertical traps are easy to deploy and monitor, but they interfere with air flow inside and outside the traps, leading to flow stagnation and scour. Elimination of these effects may be an elusive goal (Jones and Willetts, 1979; Illenberger and Rust, 1986), but frequent adjustment of

the surface in front of and at the traps by wetting or levelling (Horikawa, 1988), combined with a short sampling interval, can at least minimize problems associated with scour. We made a concerted effort in this study to identify the effects of scour in relation to surface moisture by allowing scour to occur at the traps for a 90-min period and examining their relative efficiency.

The 10 min monitoring interval was long enough to obtain measurable amounts of accretion in the traps while minimizing the amount of scour that occurred during that time. Minimal scour (<2·0 mm) occurred at the traps between 09:50 and 11:10 because there was little sand movement. No scour adjustments were made at Traps 1 to 3. Trap 4 was not adjusted for scour until after 12:20, when scour adjustments were made by filling the low areas with moist sand from the surface downwind of the trap and compacting the new surface by hand.

Seven sand samples were taken from the top 5 mm of the backbeach upwind of the traps, and one additional sample was taken on the foreshore to identify grain size characteristics, bulk moisture content and salinity. The sample locations on the backbeach were selected based on the darkness of the surface, with the assumption (later substantiated by data) that the brightest sediments were dry. The moist samples could be differentiated as light or dark, with the dark samples having the highest moisture values. A quick estimate of the amount of dry sand was made by identifying the percentage of backbeach that appeared bright (dry). One sand sample was taken from the darkest (wettest) part of the backbeach, although this sample did not represent a significant proportion of the surface. The sample taken on the foreshore was just upwind of Trap 5. The eight surface samples and six representative sediment samples taken from traps when they were removed, were placed in sealed plastic envelopes and weighed the day they were collected; they were then air-dried and reweighed to determine moisture content.

Splits of sediments were washed, dried and seived at 0·5 phi intervals. Inclusive graphic statistics were calculated according to the procedure in Folk (1974). Other splits of the samples were soaked for 48 h in known volumes of distilled water that were analysed for salinity; the percentage of salt in washed and dried sediment was then calculated. The low salt content of the sediment samples required an accurate procedure to distinguish them. Flame atomic absorption spectroscopy, using magnesium as a proxy for salinity, was used to obtain this accuracy. The ratio between magnesium and seawater is constant, allowing for conversion of magnesium values to salinity. Not all backbeach and trap samples were tested for salinity because the values determined in early runs were so low that further detailed analysis was not necessary. An estimate of the significance of salt content of surface sediments was evaluated by recalculating transport rates to account for increased critical shear velocities using data from figure 3 of Nickling and Ecclestone (1981).

Accretion and deflation of the beach surface were identified by measuring elevation changes relative to the tops of four 6·4 mm diameter pins, placed at Traps 1–4 (Figure 2). These pins were placed 1 m from the trap and were offset, so measurements did not interfere with trapping. The pins were in light moist sand upwind of Traps 1 and 3 and in dark moist sand upwind of Traps 2 and 4. The pins were emplaced at 9:40 and measured at 15:35. Elevations were taken at representative bedforms to characterize local relief.

Estimates of shear velocity (u_*) were calculated using the logarithmic relationship describing the velocity profile:

$$u_z = (u_*/\mathrm{K}) \ln (z/z_o) \tag{1}$$

where u_z is the wind speed at height z, K is the von Karman constant (assumed to be 0·4) and z_o is the roughness length. Shear velocity and roughness length were calculated from linear regression of the wind velocity profile.

The critical shear velocity ($u*_c$) was calculated using the Bagnold equation for dry sand:

$$u_{*c} = \mathrm{A}\{[(\rho_s - \rho_a)/\rho_a]\, g\, d\}^{0\cdot5} \tag{2}$$

Where A is an empirical constant with a value of 0·1, ρ_s and ρ_a are the sediment and air density, respectively, and g is the acceleration due to gravity. Air density was determined by converting the temperature monitored during each record to air density using table A.3 of Monteith (1973) and assuming dry air.

The effects of surface moisture on initiation of sand transport were estimated by calculating the critical shear velocity on a wet sand surface ($u*cw$) using the formula from Hotta *et al*. (1984):

$$u_{*cw} = \mathrm{A}\{[(\rho_s - \rho_a/\rho_a] g d\}^{0\cdot5} + 7\cdot5w \tag{3}$$

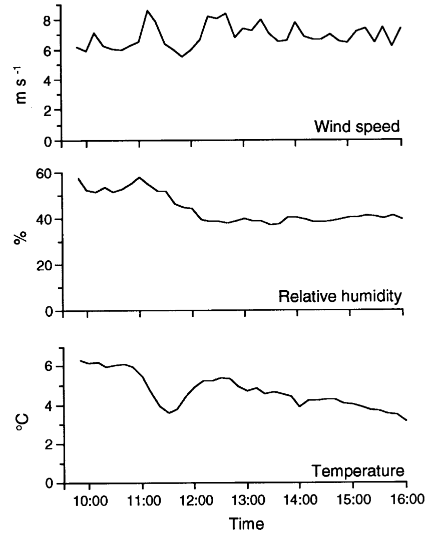

Figure 3. Wind speed, relative humidity and temperature taken from means of 10 min records sampled during times traps were in place on 16 March 1994

where w is the water content (in per cent by weight).

Calculated rates of sediment transport (q) were derived from the equation of Bagnold (1936):

$$q = \mathrm{C}\,(\rho_a/g)\,(d/D)^{0\cdot5}\,u_*^3 \tag{4}$$

where C is an empirical constant ranging from 1·5 to 2·8, and D is a reference grain diameter of 0·25. The Bagnold formula is used because it provides for comparison with previous studies that utilized similar trap design.

RESULTS

Meteorological conditions

A cold front, accompanied by rainfall, passed over the area the previous evening (15 March). Rain ended just after 07:30 on 16 March. Winds were westerly all day. Mean wind speed of 10 min records at the 6 m anemometer ranged from 5·6 to 8·6 m s^{-1} during the trap deployment (09:50 to 15:30), reaching a high at 11:10 (Figure 3). Relative humidity was greatest at 11:00 (57·7 per cent) and lowest at 13:30 (36·9 per cent), with little variation after 12:30; temperature decreased from 6·3°C at 09:50 to 3·7°C at 15:30.

Wind-speed data from the anemometers (Figure 4) expressed a log relationship. Shear velocities ranged from 0·20 to 0·32 m s^{-1} during the times when traps were deployed. These velocities were higher than the fluid threshold velocity for dry sand with a grain size as sampled at the site (0·19 m s^{-1}) calculated using Equation 2. Aeolian activity first became noticeable at 08:55; average shear velocity for the 10 min record (ending at 09:00) was 0·18 m s^{-1}.

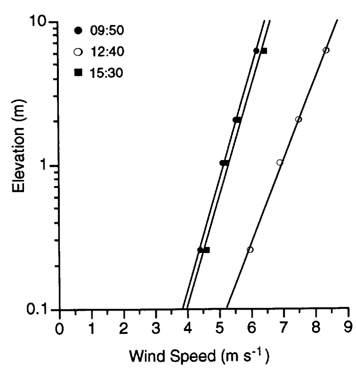

Figure 4. Wind velocity profiles taken from means of 10 min records near beginning, middle and end of period of trap deployment

Table I. Characteristics of surface sediments taken 16 March 1994.

Location	Time	Mean (phi)	Mean (mm)	Sorting (phi)	Moisture (%)	Salt (‰)
Sand surface samples						
In bright dry sand	10:05	2·57	0·168	0·27	0·10	0·14
In light moist sand	10:05	2·71	0·153	0·28	4·10	0·11
In dark moist sand	11:28	2·75	0·149	0·31	9·20	0·21
In light moist sand	11:28	2·66	0·158	0·28	2·90	
In bright dry sand	11:28	2·70	0·154	0·27	0·04	0·12
In light moist sand	15:05	2·64	0·160	0·29	3·61	0·08
In bright dry sand	15:05	2·73	0·151	0·28	0·04	0·13
Foreshore	16:30	2·51	0·176	0·36	18·42	5·00
Trap samples						
Trap 2	12:50	2·62	0·163	0·25	0·03	
Trap 3	12:50	2·64	0·160	0·26	0·02	0·11
Trap 4	12:00	2·71	0·153	0·28	0·07	
Trap 4	13:00	2·62	0·163	0·31	0·08	0·10
Trap 4	14:20	2·64	0·160	0·30	0·06	
Trap 5	15:16	2·49	0·178	0·32	0·75	1·08

Surface conditions

Surface sediments were moist everywhere on the beach in the early morning. By 09:10 conspicuous sand streamers were moving across the moist surface; shear velocity at this time was $0{\cdot}22\,\mathrm{m\,s^{-1}}$. Barchan-shaped bedforms, composed of dry sand, formed where sand streamers converged. These bedforms increased in area through time. The dry sand in the bedforms represented approximately 5 per cent of the surface area of the backbeach when traps were first emplaced (09:50); the remaining surface was composed of moist sand. By 12:50, nearly the opposite was true; approximately 90 per cent of the surface of the backbeach was characterized by dry sand. The bedforms had a height above the surface of 0·03–0·04 m at 15:00. The foreshore upwind of Trap 5 lacked conspicuous bedforms; adhesion structures with a relief of the order of millimetres were visible during monitoring.

Surface sediments in both moist and dry sand had similar mean grain sizes and sorting values that did not vary over the monitoring period (Table I). Surface samples taken in the morning indicated that moisture content of sediments comprising the dry sand in the bedforms was less than 0·1 per cent by weight. Moisture content of samples taken in the moist areas on the backbeach varied from 2·9 to 9·2 per cent. Surface moisture values in moist areas near the end of the monitoring period fell within the limits of the samples collected in the morning. The surface at Trap 4 remained moist throughout the entire sampling period.

Salt content of surface sediments on the backbeach was <0·21 per mille. The low salinity values are not surprising, given the rainfall in the morning and the offshore wind that would have reduced the likelihood of aerosols from the breaker zone reaching the backbeach. Salt content on the foreshore was much higher (5·0 per mille) because it had been inundated during the previous high tide. The effect of salinity values on the backbeach on threshold shear velocity is negligible, based on the difference between shear velocities at 0 per mille and the salinity values in Table I using figure 3 of Nickling and Ecclestone (1981).

There was 13 mm of deflation of moist sand, followed by 18 mm of accretion of dry sand, at the erosion pin placed 1 m from Trap 1 between 09:40 and 15:35. There was 3 mm of deflation near Trap 2 and 25 mm of deflation near Trap 3. Near Trap 4, there was 4 mm of deflation measured at the pin, followed by 10 mm of accretion of dry sand. This accretion zone did not reach the trap site. These differences in surface deflation can be explained, in part, by the moisture characteristics of the sediments where the pins were located. Pins near Traps 1 and 3 were located in areas of light moist sand, while pins upwind of Traps 2 and 4 were located in areas of dark moist sand. The larger deflation values near Traps 1 and 3 could be due to the lower moisture content of the light moist sand, increasing the likelihood for deflation or grain entrainment by impact with dry sand grains in transport.

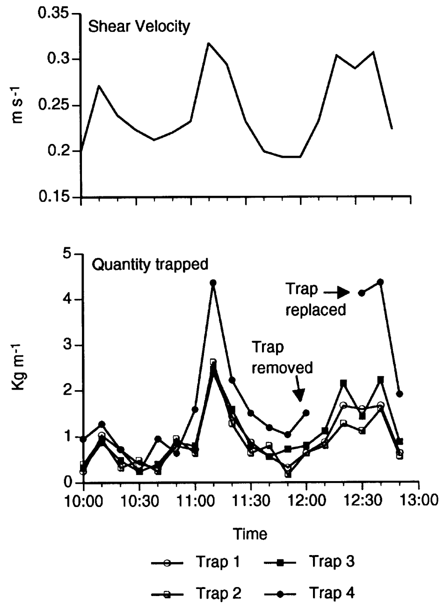

Figure 5. Changes in shear velocity and sediment trapped at Traps 1 to 4 from 10:00 to 12:50

Table II. Cumulative scour (mm) measured in front of traps from 11:20 to 12:50.

Time	Trap 1	Trap 2	Trap 3	Trap 4
11:20	4·0	2·0	2·0	<2·0
11:30	6·0	5·0	6·0	4·0
11:40	7·0	6·0	8·0	5·0
11:50	8·0	10·0	9·0	4·0
12:00	9·0	10·0	10·0	5·0
12:10	12·0	13·0	13·0	
12:20	13·0	15·0	14·0	
12:30	14·0	17·0	16·0	<2·0*
12:40	14·0	18·0	17·0	<2·0*
12:50	15·0	21·0	18·0	<2·0*

* Adjustments made for scour at this time

Effect of trap scour

The trend in the plots of sand trapped from the beginning of trap deployment to 12:50 (Figure 5) is similar for all sites, although the amount measured at Trap 4 greatly exceeds the amount at other sites after 10:50. The first major divergence between the amount of sand trapped at Traps 1–3 and Trap 4 begins with the high shear velocities that occurred between 11:00 and 11:10. Thereafter, the divergence between these traps is attributed to greater scour at Traps 1–3. The amount of scour (Table II) increased from 2 mm at Traps 2 and 3 at 11:20 to a maximum of 21 mm at Trap 2 at 12:50 when Traps 1–3 were removed. Sediment trapped at Traps 1–3 represents less than half the quantity trapped at Trap 4 during the three monitoring periods when scour was adjusted at Trap 4 and scour was greatest at the other three traps. We continued monitoring at the location of Trap 4 after 12:50 because trapping efficiency was greatest at this location and there was less potential for scour, making subsequent scour adjustments easier.

Effect of surface drying

Evaporation is an important influence when the shear velocity is less than the wet threshold velocity but greater than the dry threshold velocity (Hotta *et al.*, 1984). Critical shear velocities for the moist surface were

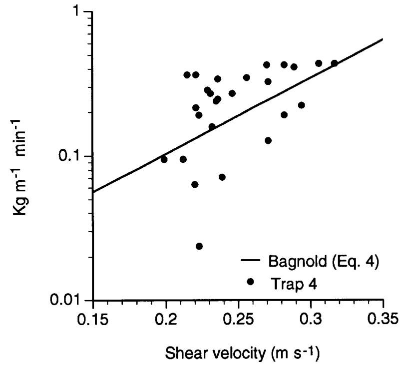

Figure 6. Measured rates and calculated rates as a function of shear velocity from sand trapped at Trap 4 (except for a period between 11:30 and 12:00 when scour was greater than 2·0 mm)

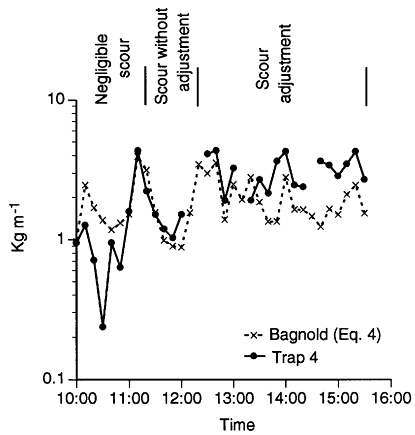

Figure 7. Measured rates and calculated rates of transport over time, from sand trapped at Trap 4. The trap was emptied and replaced between 12:00 and 12:20, 13:00 and 13:10 and between 14:20 and 14:30. Measurement error for measured rates is represented by diameter of symbols

calculated using Equation 3 and moisture values for the three samples taken from the backbeach in light moist sand (Table I). Results indicate that critical shear velocities for the moist surface exceed measured shear velocities for all 10 min records. Transport could have been initiated on moist areas of the beach early in the morning during gusts, but transport would not be expected to reach its full potential.

Trap 4 was monitored for 2·5 h longer than the other three traps, and data from this trap provide insight to the effect of surface drying. Figure 6 shows the relationship between shear velocities, measured rates and calculated rates (from Equation 4) at Trap 4 when scour was not a problem. There is slightly better agreement between measured rates and calculated rates at higher shear velocities.

Large divergences between the measured rates and the calculated rates occurred prior to 11:10 when scour was minimal (Figure 7). The differences between measured and calculated rates are small between 11:10 and 12:00 when scour was allowed to occur (Figure 7 and Table II). The increase in measured rates relative to calculated rates after 12:50 (Figure 7), when wind speeds show a slight increase (Figure 3), is attributed to greater amounts of dry sand on the beach that resulted in increased spatial coverage of bedforms.

Transport rates on the moist foreshore were higher than on the backbeach. Calculated critical shear velocity for the foreshore sediments (using Equation 3) was $1{\cdot}54\,m\,s^{-1}$. Theoretically, sand corresponding to the mean grain size could not be entrained by wind from the surface of the foreshore. The rate of sand trapped here during the two sampling periods the trap was in place ($0{\cdot}41\,kg\,m^{-1}\,min^{-1}$) was higher than the rate at Trap 4 during the same interval ($0{\cdot}32\,kg\,m^{-1}\,min^{-1}$), indicating that the wet foreshore was a highly efficient transport surface for sediment delivered to it from the backbeach, where dry sediment had accumulated by this time.

DISCUSSION

Surface moisture values of the backbeach sediments at Wildwood fell below the upper limits identified by Kuhlman (1958) and Sarre (1988), but the highest value was higher than values reported by Svasek and Terwindt (1974). Hotta *et al*. (1984) assume water content of 0·2 to 0·6 per cent for dry sand under natural conditions. The values of dry sand monitored in our study were slightly less than these.

Speed of sediment drying via evaporation may be a more important control on entrainment than moisture content (Sherman, 1990a). Estimating transport rates and their relationship to moisture content of surface sediments in the field is obscured by the drying process. Once dry sand is in the transport system, it is difficult to determine whether sediment that is trapped originated from a moist surface or from dry sand bedforms deposited on top of the moist surface, especially because sand entrained from a moist surface (moisture content of 3 to 4 per cent) can possess moisture levels of dry sand after being transported less than 10 m from where it was entrained (Hotta *et al*., 1984). Based on shear velocities, moisture content would have to drop below 2 per cent for sediment to be entrained by the mean wind speeds recorded prior to 11:00 (calculated using Equation 3). Data from surface samples indicate that the sediment surfaces between the bedforms and underlying the bedforms were not this dry. Thus, transport condition 1 (moist sand entrained from a moist surface) did not occur under mean wind speeds but may have occurred during gusts. Deflation measured in areas of moist sand during our study indicated that sediment from the initially moist surface was released to the air stream during the day. Condition 2 (sand entrained through surface drying with subsequent movement as streamers across a moist surface) did occur. It is possible that at least part of the sand in transport at 09:50 was initiated in the small patches of dry sand, signifying commencement of processes operative in condition 3.

Trapping rates during our study, for shear velocities between 0·20 and 0·40 m s^{-1}, are within the range of measured values reported by Svasek and Terwindt (1974) but lower than the rates measured by Sarre (1988). Svasek and Terwindt (1974) found no direct relationship between the shear velocity and measured rates of sand transport for velocities similar to those measured in this study (<0·4 m s^{-1}). Our results also show little relationship between these two variables.

Speed of drying is difficult to measure in the field, but it may be evaluated conceptually in terms of the time-dependent moisture content of surface sediments. Time-dependent changes in surface moisture offer an explanation for both the range in measured rates for a given shear velocity and the degree of correspondence with calculated rates (Figure 6). Our results indicate that measured rates were high relative to calculated rates when a greater portion of the surface was composed of dry sand and there was greater spatial coverage in bedforms (Figure 7). Blumberg and Greeley (1993) showed that, for a given shear velocity, a rough surface can reduce aeolian transport of saltating particles. In the afternoon, when the areal extent of bedforms at Wildwood comprised 95 per cent of the surface, the measured transport rate increased relative to the calculated rate, indicating that the greater quantity of dry sediment may be the important control.

During trap monitoring, the transport conditions on the backbeach changed from condition 2 (intermittent transport by sand streamers) to condition 3 (transport off dry sand bedforms) in response to increased spatial coverage of the dry sand bedforms relative to the moist surface. Sand streamers, typical of condition 2, still occurred at this time. At low shear velocities, differences between measured and calculated transport rates over moist surfaces have been attributed to the spatial variability in moisture content (Svasek and Terwindt, 1974; Sarre, 1988). Presenting point measurements of moisture content as average values can misrepresent complex surface conditions in environments where there is high moisture variation (Sarre, 1988). Point measurements that are weighted for proportion of spatial coverage in the source area may better represent transport potential and are suggested for future studies.

Many previous beach studies indicate that calculated rates of sediment transport can be higher than measured rates (e.g. Bauer *et al*., 1990; Davidson-Arnott and Law, 1990; Nordstrom and Jackson, 1992). Source widths are critical to understanding these lower measured rates. Svasek and Terwindt (1974) and Greeley *et al*. (1996) report higher measured than calculated rates of transport for some of their sampling runs when source widths are great. The greater source area of dry sand in the afternoon during our study contributes to the higher measured rates relative to the calculated rates. These rates may appear especially high given the inefficiencies

of vertical cylindrical traps, but the traps have high efficiency relative to more aerodynamic vertical traps at low wind speeds (Gares *et al*., 1996). The relatively low wind speeds, combined with emplacement of Trap 4 on a moist surface and adjustment for scour every 10 min may have reduced some of the inefficiencies, contributing to the relatively high measured rates in our study.

The high rate of transport across the foreshore (revealed at Trap 5) helps confirm Borówka's (1980) observation that transport rates can be relatively higher over a smooth humid surface than a dry surface with greater roughness elements. Svasek and Terwindt (1974) observed that sand delivered from an upwind source can overcome increased moisture effects on downwind surfaces, and (Sherman, 1990b) found that dry sand injected on a wet sand surface moved readily when no transport was initiated on that surface. Data from the trap on the foreshore indicate that measured rates can be high with moisture values near 18 per cent and relatively low shear velocities. The high rate of transport on the foreshore is due to the delivery of sediment from the large area of dry sand upwind (condition 4), and does not reflect the likelihood for entrainment within a source area with moisture values of 18 per cent or with a salinity of 5 per mille.

The moisture of sediments in the trap on the foreshore, in the wettest portion of the beach, is less than the highest moisture value (1·0 per cent) in sediments trapped by Kuhlman (1958) but is considerably less than the values reported by Sarre (1990) for traps placed on damp and wet sand. The higher moisture values in the trap on the foreshore (relative to backbeach samples) could indicate that sand from the backbeach picked up moisture as it moved across the foreshore or that wetted foreshore sand was entrained. The sand trapped in our study may be drier than Sarre's because it contains saltating grains from the dry sand surface upwind of the foreshore, underscoring the importance of determining the location of the source of sediments in transport across a moist surface.

CONCLUSIONS

Transport rates in the field are highly variable through both space and time. The drying process obscures estimates of transport rates and their relationship to moisture levels because surface moisture may delay optimum transport conditions for several hours following initiation of transport. An explanation for both the decrease in the range of measured rates for a given shear velocity and the degree of correspondence with calculated rates through time lies in determining the time-dependent moisture content.

Although we have conceptualized sediment entrainment and transport across moist surfaces by five conditions, only three of these (*in situ* drying with transport as sand streamers, entrainment and transport from dry bedforms superposed on a moist surface, and transport across a moist surface from a dry upwind source) were common during the low-speed winds.

The first condition describes a surface that is intermittently moist and dry, although given present sampling constraints (estimation by bulk moisture values), the sediments may appear to remain moist. The increased spatial coverage of dry sand bedforms relative to the moist surface and the increase in measured rates imply that quantification of dry surface areas can be used to estimate the effect of drying on transport. Point measurements of surface moisture that are not weighted for proportion of spatial coverage in the source area and evaluated for changes through time may misrepresent transport potential. Determination of the location of sources of sediment in transport across a moist surface is also important because sand delivered from an upwind source can overcome increased moisture effects on downwind surfaces.

ACKNOWLEDGEMENTS

This project was funded by a research grant from the New Jersey Institute of Technology. We are grateful to Thomas Flud and the community of Wildwood for permission to conduct the experiment on the beach, to Bas Arens, Dennis Munhall, Elaine Brenner and Steve Merlino for assistance in the field, and to Christine Rothfuss and James Ross for laboratory analysis. We also thank Rob Sherrell for use of his laboratory facilities. This is contribution number 95–25 of the Rutgers University Institute of Marine and Coastal Sciences.

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